EXPERIMENTAL INVESTIGATION ON THE TRUE LOCAL FATIGUE STRENGTH OF SHELL-CORE SHELL LAYERED, INJECTION MOULDED SPECIMENS OF SHORT FIBRE REINFORCED POLYAMIDE

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Abstract
Injection moulded plates made of short fibre reinforced polymers are often used to study the effect of fibre orientation on mechanical properties. Using specimens cut out of these plates with different orientations with respect to the injection flow, off axis tests can be performed. However, injection moulded plates have a characteristic layered structure, with different fibre orientations through the thickness, resulting into the well-known shell-core-shell structure. This makes it difficult to separate the contributions of each layer. In this work, a preliminary study on the fatigue behaviour each layer is presented. Specimens were machined by milling, leaving only the shell layer in specimens extracted from plates at 0° and 90° orientations. Results are discussed in the light of finite element analysis, where the layered microstructure is considered. For the simulations, fibre orientation distributions obtained experimentally are used and stresses in each layer are evaluated. Finally, local stresses are compared with local strength values obtained experimentally.

1. Introduction

In a previous work [1], a local stress analysis of the specimens used in Ref. [2] to study the effect of fibre orientation on the fatigue behaviour of a short fibre reinforced polyamide was presented and discussed. Finite element analysis of the specimens was conducted, taking into account the effect of the through thickness variation of the fibre orientation. In fact, the specimens were characterized by the skin-core-skin layered structure usually encountered in injection moulded plaques, as proven by micro computed tomography [3] and by the optical method [1, 4].
In [1] it was found that stresses in the shell layer differed from those in the core layer. However, even after the observation of fracture surfaces, it was difficult to understand where the most critical conditions for crack nucleation were met for each orientation of the specimens, particularly in the case of 0° and 90° orientations. Knowledge of this would have allowed for determining the true local fatigue strength, for the material having the fibre orientation of the shell layer and for that having the orientation found in the core layer
To investigate on this aspect, some specimens belonging to the batch used in [2] were machined to remove the core layer and preserve the shell one, to test only the remaining portion of the specimen. These machined specimens have uniform fibre orientation through the thickness and allow for assessing

the fatigue strength of the material having that fibre orientation, without the disturbing effects of the presence of other layers with different fibre orientation, that prevented form assessing the true fatigue strength of the layer based on the local stress analysis reported in [1].
In this work, results of the fatigue tests are presented and discussed in the light of the results of a local stress analysis, in which the local stresses are evaluated using the fibre orientation distribution obtained experimentally, whereas previous results reported in Ref. [1] were obtained by process simulation, although validated on experimental fibre orientation values.

2. Experimental

Specimens used for the work presented herein belonged to the same batch of those used in [2]. They were obtained by machining of injection moulded plates and they were cut out of them with different orientations with reference to the longitudinal axis of the plate. In this work, some specimens oriented at 0° and 90° were machined to obtain specimens having only the shell layer. The thickness of 1.1 mm of the new specimen was chosen based on the analysis of the fibre orientation reported in [1].

Only 5 specimens remained of the original batch with orientation at 0°, whereas more numerous specimens cut at 90° were left. Tests were conducted using a servo hydraulic testing machine of 25 kN capacity, in load control mode, with a frequency of 4 Hz and a stress ratio R = 0.1, like in the previous tests reported in [2].

Results of the fatigue tests are reported in the graph of Figure 1, where the maximum applied stress is plotted against the number of cycles to failure. Parameters of the interpolating curve (Basquin equation $\sigma_{max} = \sigma'_f N_f^{-b}$) and values of σ_{10^6}, the fatigue strength at 10^6 cycles, are reported in Table 1.

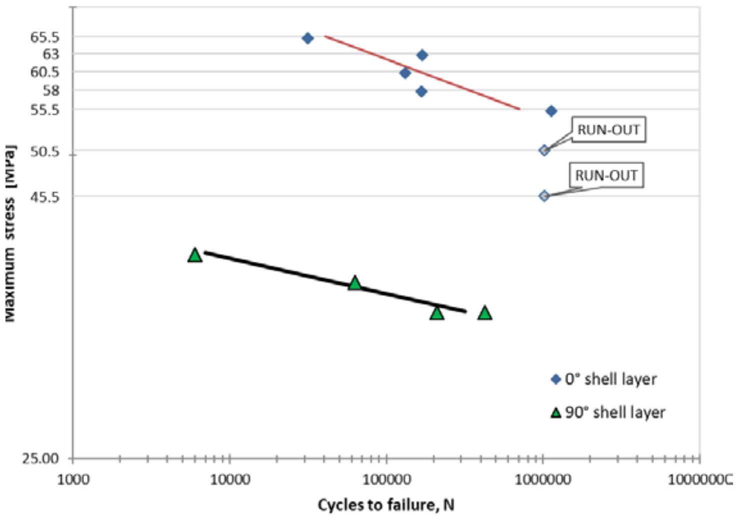

Figure 1. S-N curve of the machined specimens

Results are superimposed to results of Ref.[2] in Figure 2. It appears clearly that the strength of both 0° and 90° milled specimens is too high with respect to the results previously obtained. More in detail, the strength of the milled 90° specimens was expected to be lower than that of the integer 90° specimens, because of the absence of the core layer, which is stiffer and stronger because the fibres are parallel to the applied stress. Moreover, although the strength of the milled 0° specimens was expected to be higher than that of the integer 0° specimens, because of the presence of the weaker core with fibre oriented perpendicular to the applied stress, the strength appears to be too high. The difference was mainly ascribed to the variation of the water content, which was reduced to 1.65 % from the original 2.2 %.

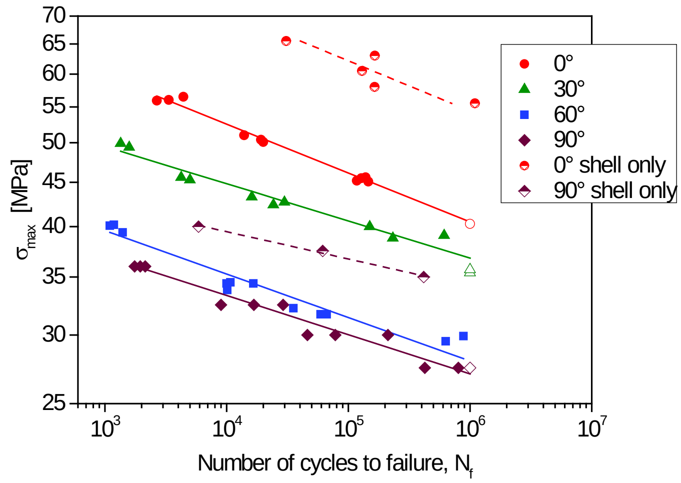

Figure 2. S-N curve of the machined specimens superimposed to the results of [2]

To account for the effect of this variation of the water content, additional tests were conducted on integer 90° specimens. The results are shown in Figure 3. It appears clearly that the S-N curves of the 0° milled and integer specimens are now very close to each other, having the specimens approximately the same water content. Then, results were normalized, by multiplying the values of the stresses applied to the milled specimens by the ratio of the fatigue strength at 10^6 cycles of the newly tested 90° integer specimens and that of the 90° specimens of Ref.[2]. The new position of the S-N curves is shown in Figure 4, superimposed to the results of Ref.[2]. After this normalization, the S-N curve of the milled 90° specimens is slightly lower than that of the integer ones and the S-N curve of the milled 0° specimens is higher than that of the integer 0° specimens. Values of the corresponding parameters of the Basquin equations and of the strength at 10^6 cycles are reported in Table 1. The local strength of the material with fibres oriented at 0° is estimated as 3 MPa higher than that obtained using the integer 0° specimens. These values were final compared with stresses evaluated numerically by finite element (FE) simulation.

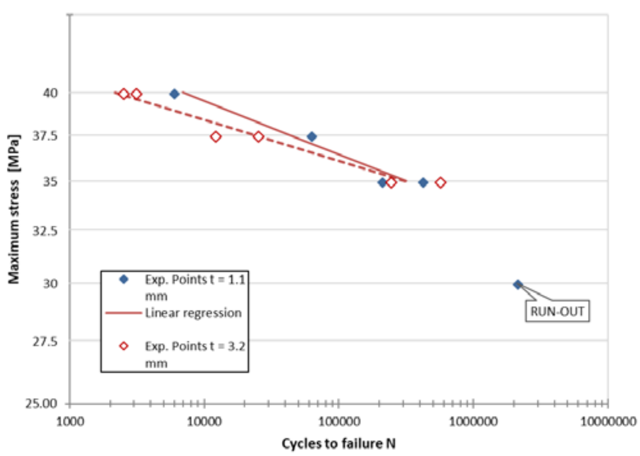

Figure 3. S-N curve of the machined specimens superimposed to the newly tested 90° specimens

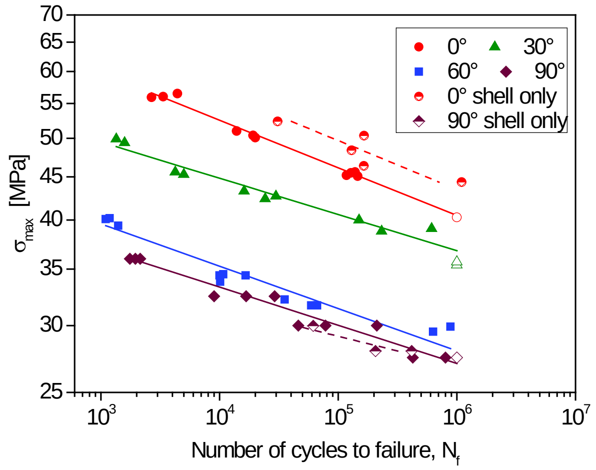

Figure 4. Normalized S-N curve of the machined specimens superimposed to the results of [2]

Table 1. Fatigue strength values at 10^6 cycles.

Specimen Type	σ'_f (MPa)	b (-)	σ_{10^6} (MPa)	Normalized σ_{10^6} (MPa)
0° [2]	88.5	0.057	40.3	-
90° [2]	50.5	0.045	27.1	-
0° (milled)	121.0	0.058	54.4	43.5
90° (milled)	54.5	0.035	33.6	26.9
90° same as [2], newly tested	49.3	0.027	33.9	-

3. Numerical analysis

Linear elastic FE analyses of the 0° and 90° specimens were performed using Abaqus 6.14 and Digimat 2017.1 software packages. Linear 4 node shell elements were used. To take into account the effect of the fibre orientation (FO) upon elasticity of the material, FO values obtained by measurements (reported in [1] and obtained by the optical method [5]) were mapped onto the structural mesh using Digimat Map package. This allowed for evaluating the local values of the stiffness matrix, assuming that each element behaves like a composite laminate, with each lamina having the properties of an orthotropic material. The elastic constants were related to the FO orientation tensor components by a Mori-Tanaka homogenization scheme. Specimens were loaded with an axial load corresponding to the product of the fatigue strength at 10^6 cycles and the nominal area of the cross section. Specimens's tabs were constrained rigidly to simulate the effect of the grips.

3.1. Fibre orientation

Experimental FO data included values of the a_{11}, a_{22} a_{33} and a_{13} components of the fibre orientation tensor [6]. To define the FO in the FE model, values of the a_{12} components were also needed. Values of a_{12} cannot be obtained by the experimental method based on optical observation of the cross sections of the fibres, as the sign of the angle that the fibre forms with the normal to the section plane cannot be determined. Therefore, values of a_{12} were determined by a best fit approach. It consisted in optimizing the values of a_{12} so that in each layer values of the a_{11} and a_{22} components obtained by rotation of the FO tensor were as close as possible to the experimental one. The complete set of FO tensor component values are plotted in Figure 5. The comparison of the FO tensor components obtained by rotation with experimental ones is reported in Figure 6.

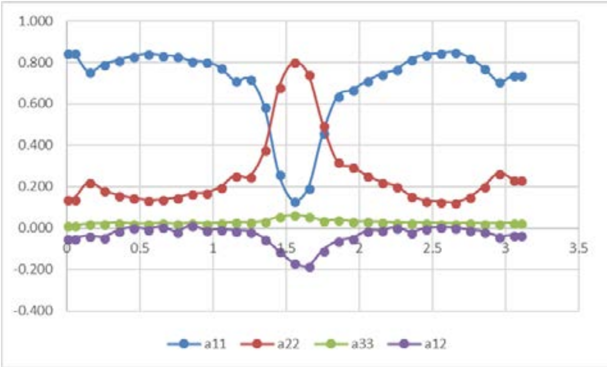

Figure 5. Components of the orientation tensor (a_{11}, a_{22}, a_{33} measured; a_{12} inferred by optimization)

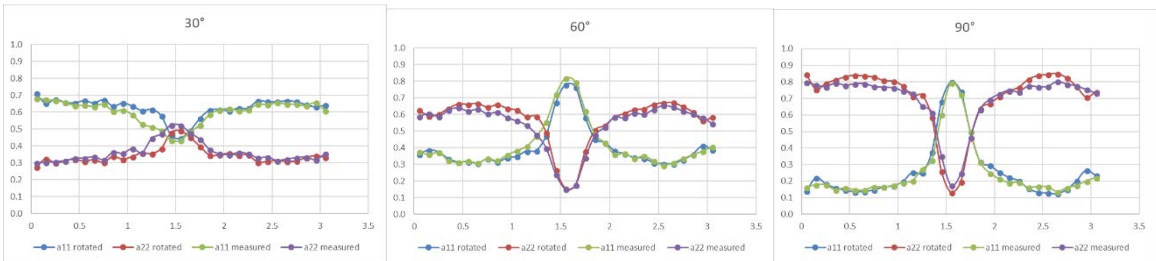

Figure 6. Components of the orientation tensor a_{11} and a_{22} obtained by rotation of the 0° tensor, using inferred values of a_{12}, compared with measured ones

3.2. Result of finite element analyses

Results of the FE analyses of the 0° and 90° specimen are reported in Figure 7 and Figure 8, respectively. Stresses are plotted with reference to the material's orientations. Local σ_{11} stresses in the shell layer are plotted in Figure 7a, while values of the σ_{22} stress of the core layer are reported in Figure 7b. Average values evaluated over the gauge section are reported in Table 2.

Average σ_{11} stress in the shell layer equals 47 MPa and slightly exceeds the local fatigue strength of 43.5 MPa evaluated by tests on milled specimens. Conversely, the σ_{22} average stress of 13.7 MPa in the core layer appears to be considerably lower than the fatigue strength of 26.9 MPa evaluated experimentally. Therefore, combining experiments on milled specimens with numerical analyses, it can be concluded that the true strength of the material was probably underestimated by tests reported in Ref. [2]. By excluding the contribution of the core layer, numerical results are in good agreement with experimental results, although they must be considered as preliminary and more data are needed to confirm the effect of water content and validate the applied normalization method.

a)

b)

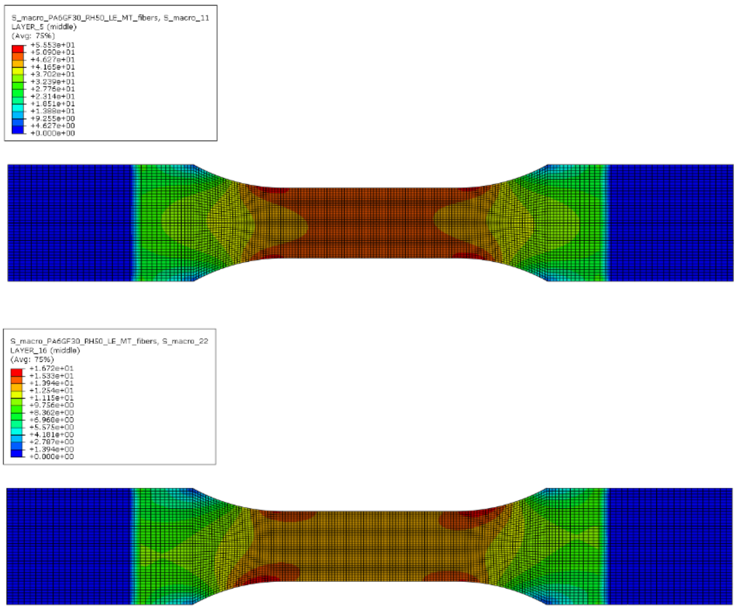

Figure 7. Stresses in the 0° specimen: a) shell layer; b) core layer
a) shell layer; b) core layer

a)

b)

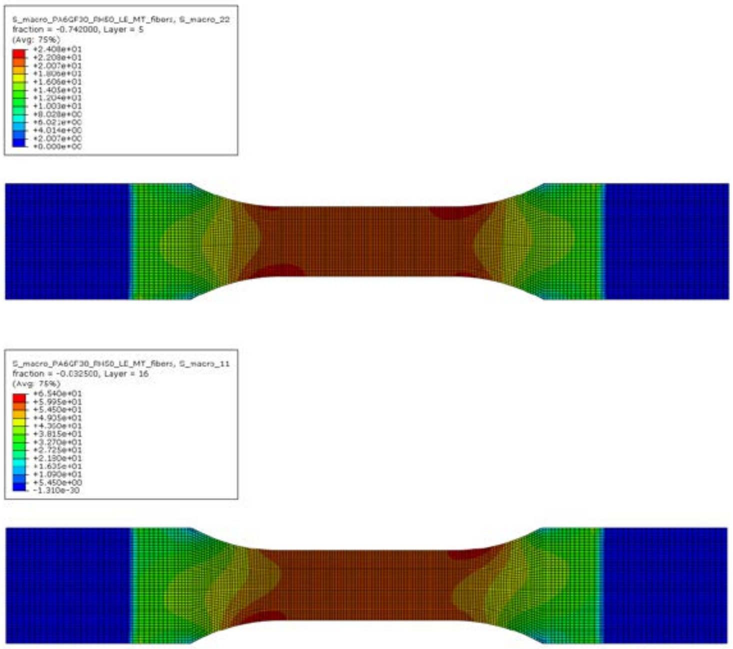

Figure 8. Stresses in the 90° specimen: a) shell layer; b) core layer

In the 90° specimens, the σ_{11} average stress of 56.7 MPa in the core layer (Figure 8b) largely exceeds the fatigue strength evaluated experimentally. This suggests that the core layer might have degraded rapidly during the early stages of the fatigue tests, thus presumably leading to a progressive load transfer to the shell layer. In this layer, the initial value of the average σ_{11} stress of 21.5 MPa (Figure 8a) is lower than the fatigue strength of 26.9 MPa estimated experimentally. The load transfer might have increased the value of the σ_{11} stress, thus explaining the final failure for an applied stress larger than the one initially evaluated. In any case, these observations allow for concluding that also in the case of the 90° specimens, a more accurate determination of the fatigue strength in the 2 direction of the material with uniform FO can be obtained by tests conducted on milled specimens.

Table 1. Stresses in the shell and core layers of the 0° and 90° specimens

Specimen	Layer	Avg σ_{11}	Avg σ_{22}
0°	Shell	47	-
0°	Core	-	13.7
90°	Shell	-	21.5
90°	Core	56.7	-

4. Conclusions

Based on the results reported herein, the following conclusions can be drawn:

- tests on specimens milled to extract the shell layer appear to be feasible;
- the presence of a core layer in specimens of ref [2] extracted from injection moulded plates presumably led to underestimating the fatigue strength of the material with uniform FO in the 0° direction and to slightly overestimating the fatigue strength of the material with uniform FO in the 90° direction;
- the FE simulations with the definition of the local material's properties based on experimental values of the FO orientation tensor yielded results in fair agreement with experiments and indicate that the evaluation of local stresses allows for a more accurate interpretation of the results of fatigue tests, with the aim of estimating the true local strength values.

Results presented herein must be considered as preliminary, as more fatigue tests are required to obtain S-N curves allowing for more accurate quantitative comparison. Numerical analyses will be extended to the 30° and 60° cases.

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